

An Optical Ultrahigh Resolution Spectrograph for Use with Adaptive Optics

J. Ge, B. Jacobsen, J.R.P. Angel, N. Woolf, J. H. Black, M. Lloyd-Hart, P. Gray
Center for Astronomical Adaptive Optics, Steward Observatory, University of Arizona,
Tucson, AZ 85721

R. Q. Fugate
Starfire Optical Range, U. S. Airforce Phillips Lab, Kirtland AFB, NM 87117

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ABSTRACT

A prototype ultrahigh resolution spectrograph has been built with an adaptive optics telescope. It provides 250,000 resolving power, 300 Å wavelength coverage and 0.8% efficiency.

A prototype optical wavelength ultrahigh resolution echelle cross-dispersed spectrograph has been tested at the Starfire Optical Range (SOR) 1.5 m telescope (Woolf et al. 1995; Ge et al. 1996). To our knowledge this is the first high resolution spectrograph to take advantage of the diffraction limited images produced by an adaptive optics system. Because of the sharpened images produced by the adaptive optics at visible wavelength, about $r_0/D \sim 1/15$ in the seeing-dominant domain, the narrow slits necessary for high resolution can be used without a large loss of light. This is a great advantage when compared with conventional high resolution spectrographs (e.g. Lambert et al. 1990; Diego et al. 1995). In addition, the smaller image widths inherent with the adaptive optics system allow the orders to be spaced closer together on the chip, allowing more orders to be observed simultaneously.

The main part of the spectrograph layout at the Coudé room of the SOR is shown in Figure 1. A $242 \times 116 \text{ mm}^2$ Milton Roy R2 echelle grating with 23.2 gr mm^{-1} and a blaze angle of 63.5° was used to provide the main dispersion. Theoretical resolution of this grating is 500,000 in the I band, 600,000 in the R band and 800,000 in the V band. Cross dispersion was provided by an 8° apex angle BK7 prism used in double pass configuration. The grating was illuminated in quasi-Littrow mode with a small ($\sim 0.25^\circ$) out-of-plane tilt. Collimation was provided by a large off-axis parabola with a focal length of 6 m. A large folding flat was used to reduce the overall length of the spectrograph. A Loral back-illuminated CCD with $15 \mu\text{m}$ pixels and antireflection (AR) coating in a 2048×2048 format was proposed. The pixel size was sufficient for Nyquist sampling. The spectral format for the spectrograph is shown in Figure 2. The central box is the CCD’s physical size ($30 \times 30 \text{ mm}^2$), which can cover about 90 echelle orders, corresponding to a wavelength range of 0.47 to $1 \mu\text{m}$ (or from the 163rd to the 76th order), with a width of $\sim 8 \text{ \AA}$ per order. The 30 mm length of the CCD is such that 11 exposures are needed to obtain a complete coverage of all the orders.

We have conducted two observation runs at the SOR 1.5 m telescope, one in June and one in November of 1995. Here we briefly report the results.

At the SOR two different wavelength bands are available (but not simultaneously), the “Blue” leg ($0.47\text{--}0.7 \mu\text{m}$) and the “Red” leg ($0.7\text{--}1.0 \mu\text{m}$). Figure 3 and 4 show parts of spectra obtained for Vega for the Blue and Red legs respectively. They were taken in June 1995 with a 2048×2048 Kodak thermo-electrically cooled CCD with $9 \mu\text{m}$ pixels. Figure 5 is a reduced spectrum of a He-Ne laser obtained during the same run; the separate modes are clearly resolved indicating a resolving power of about 660,000 at 6328 \AA , which is very close to the predicted resolution of 680,000. However, stellar observations from Vega and other bright stars give a much lower resolution (approximately 250,000) due to the use of a larger slit (about $100 \mu\text{m}$) (Figure 6). Due to the use of a smaller Kodak CCD (because of electronics problems with the prepared Loral CCD), the wavelength coverages for the Blue and Red legs are approximately 300 \AA and 200 \AA , respectively.

The spectrograph has 11 reflecting and 10 transmitting surfaces (including a relay

system before the slit). This leads to large photon losses. Total efficiency for the June run, including sky and telescope transmission, spectrograph losses, and CCD quantum efficiency, was only about 0.3% near the peak of the blaze. Improvements in coatings, however, by November increased the total efficiency to approximately 0.8% (Figure 7).

Table 1 shows a comparison between different ultrahigh resolution spectrographs, and includes the proposed spectrograph for the SOR 3.5 m telescope. High resolution spectrographs mated with adaptive optics can make great gains in both throughput and wavelength coverage over conventional spectrographs.

Table 1. Comparison between Different Ultrahigh Spectrographs in the World

Name	McDonald (2.7 m) ^a	AAT (3.8 m) UHRF ^b	SOR 1.5 m	SOR 3.5 m (planned)
Resolution	$5\text{--}6 \times 10^5$	9.9×10^5	2.5×10^5 ^f	7.7×10^5
Total efficiency at V band	0.045%	0.32%	0.8%	4% ^g
CCD	TI-2 800×800	Thomson 1024×1024	Kodak 2048×2048	Loral 4096×2048
Pixel Size (μm)	15	19	9	15
Readout Noise (e^-)	15	3.9	12.2	5
Pixel Number/Res. Element	8	2.4	10.3	2
Wavelength Coverage (\AA)	1.2	2.5	$200,270,500$ ^e	1300
Working Wavelength(\AA)	3,300-8000 ^c	3,000-11,000	4,000-10,000	5,000-10,000
V Magnitude limit (mag) ^d	4.4	7.8	7.4	11.1

^a The information on McDonald Coudé Echelle is based on Hobbs & Welty (1991) and Tull et al. (1995).

^b The information on AAT UHRF is based on Diego et al. (1995).

^c From Cardelli (1995).

^d Based on the same readout noise, $5 \text{ e}^-/\text{pixel}$, same pixel size, $15 \mu\text{m}$, 30 mins exposure and $\text{S/N} = 30$ per pixel.

^e 200 \AA for Red Leg spectrum coverage ($7,000\text{--}10,000 \text{ \AA}$) with Kodak $2\text{k} \times 2\text{k}$ CCD with $9 \mu\text{m}$ pixels, 270 \AA for Blue Leg spectrum coverage ($4,700\text{--}7,000 \text{ \AA}$) with Kodak $2\text{k} \times 2\text{k}$ CCD. 500 \AA for Blue Leg spectrum coverage with Lesser’s 2048×2048 CCD with $15 \mu\text{m}$ pixels.

^f Due to the slitwidth of a temporary slit ($\sim 100 \mu\text{m}$), we cannot narrow it down to the $40 \mu\text{m}$ width needed to reach more than half million resolution.

^g The efficiency has included the increase of the 3.5 m telescope/AO transmission, about 2.5 times 1.5 m telescope transmission (Fugate 1995, private communication), and the increase of the Loral CCD QE, about 2 times the Kodak CCD QE.

REFERENCES

- Cardelli, J. A., 1995, in Laboratory and Astronomical High Resolution Spectra, ASP Conf. Series, Vol. 81. 411.
- Diego, F., et al. 1995, MNRAS, 272, 323
- Ge, J., et al. 1996, in Preparation
- Hobbs, L. M., & Welty, D. E., 1991, ApJ, 368, 426
- Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L., 1984, Solar Flux Atlas from 296 to 1300 nm,
- Lambert, D. L., Sheffer, Y., & Crane, P., 1990, ApJ, 359, L19

Tull, R. G., et al. 1995, *PASP*, 107, 251

Woolf, N., et al. 1995, *Proc. SPIE Conference on Adaptive Optical Systems and Applications*, 2534, Eds. R. K. Tyson & R. Q. Fugate

Figure Captions

Figure 1 – Optical layout of the SOR cross-dispersed echelle spectrograph.

Figure 2 – Echellogram for the SOR cross-dispersed echelle spectrograph. Wavelength increases from left to right and from bottom to top. Several order numbers and central wavelengths are marked. The central box is the size for the Loral 2kx2k CCD with $15\ \mu\text{m}$ square pixels. The order separations and central wavelengths are measured from the observation data obtained at SOR in June and November, 1995.

Figure 3 – Vega spectra from SOR 1.5 m telescope/AO “Red” leg with SOR Kodak 2kx2k CCD with $9\ \mu\text{m}$ square pixels. Several orders and wavelengths are marked.

Figure 4 – Vega spectra from SOR 1.5 m telescope/AO “Blue” leg with the Kodak CCD.

Figure 5 – The spectral profile of the He-Ne laser at 632.8 nm. where 4 adjacent laser modes separated by 0.00618 nm are clearly resolved. The FWHM resolution is 3.9 pixels or $36\ \mu\text{m}$ corresponding to a resolving power of 660,000.

Figure 6 – Part of the telluric O_2 absorption lines in the Vega spectrum obtained with the SOR echelle spectrograph. It is compared to the Kurucz et al. (1984) solar spectrum which was smoothed to resolution of 260,000 via convolution with Gaussian function. Two sets of telluric lines show similar line profiles, indicating Vega spectral resolution of about 250,000.

Figure 7 – Actually achieved total combined efficiency of the SOR echelle spectrograph as a function of wavelength, which includes the sky transmission, telescope/AO transmission, Strehl ratio of the image, slit loss and the spectrograph + Kodak CCD. The quick fall-offs at wavelength longer than $8500\ \text{\AA}$ and shorter than $5500\ \text{\AA}$ are mainly caused by the fall-offs of the Kodak CCD QE at these wavelength ranges.

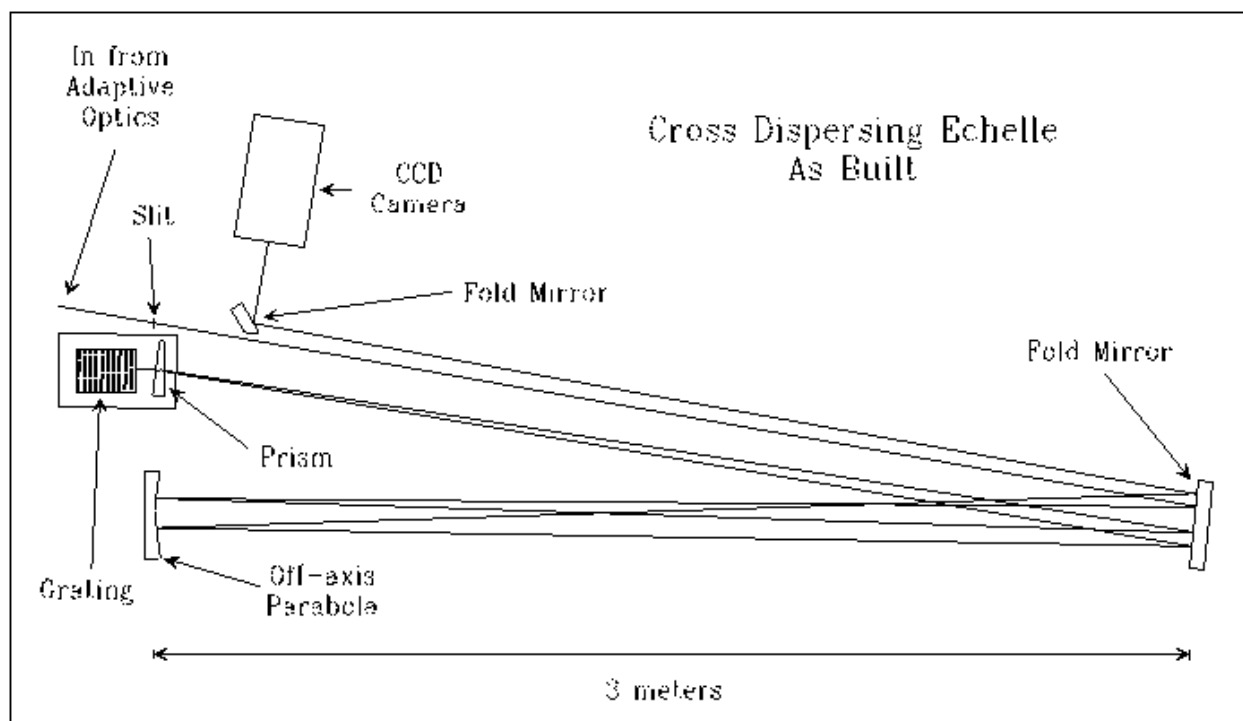


Fig. 1.—

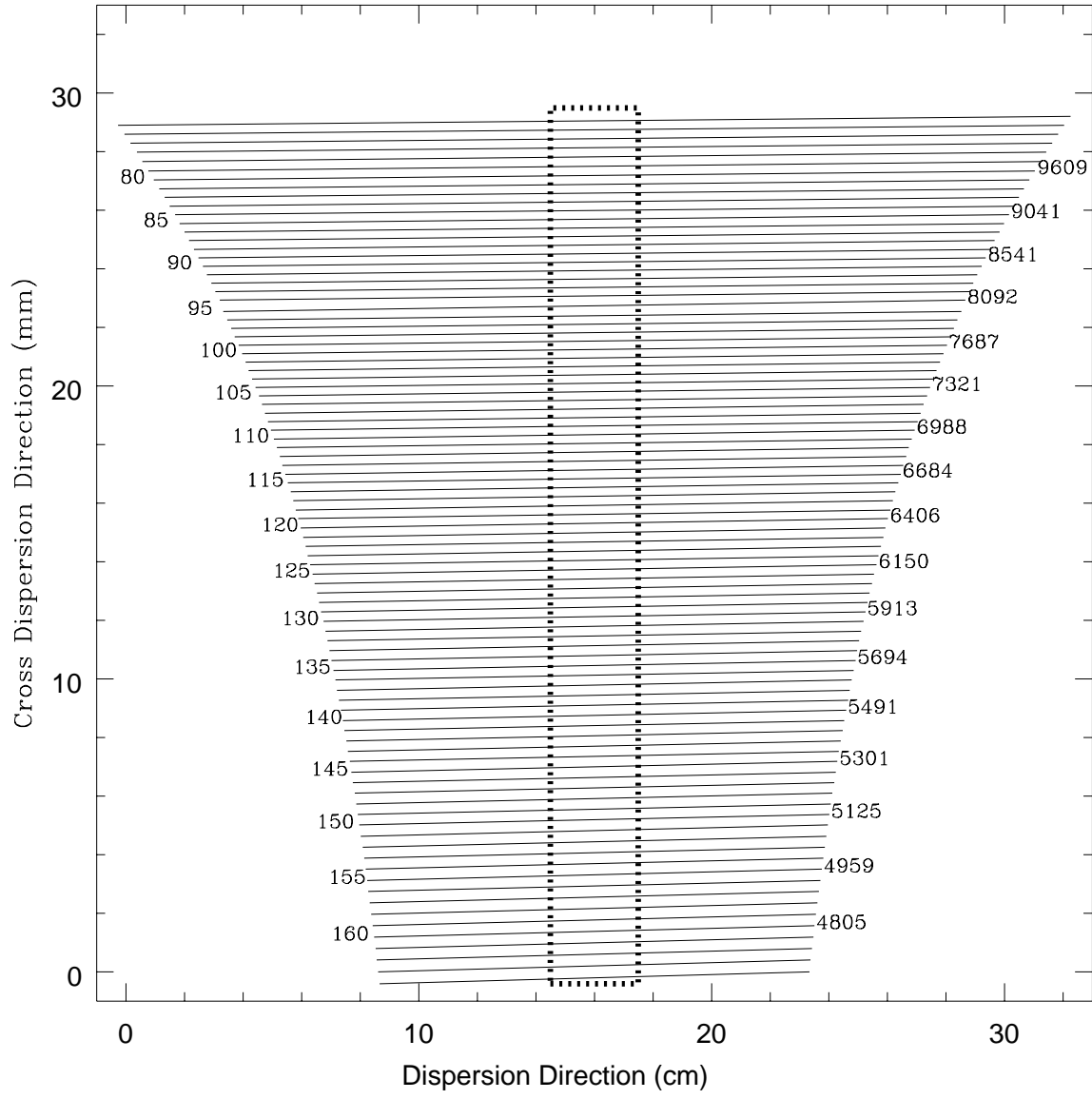


Fig. 2.—

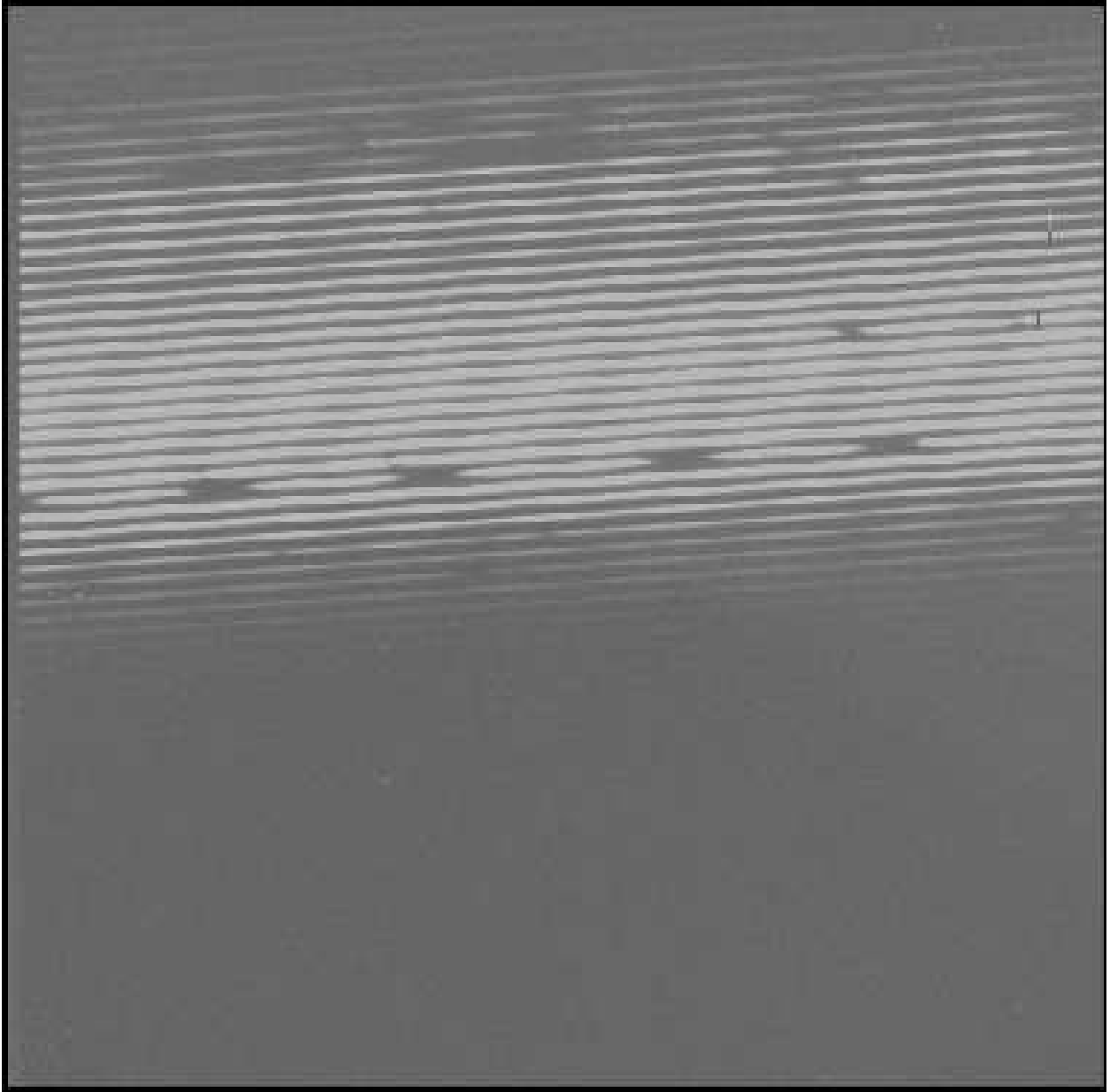


Fig. 3.—

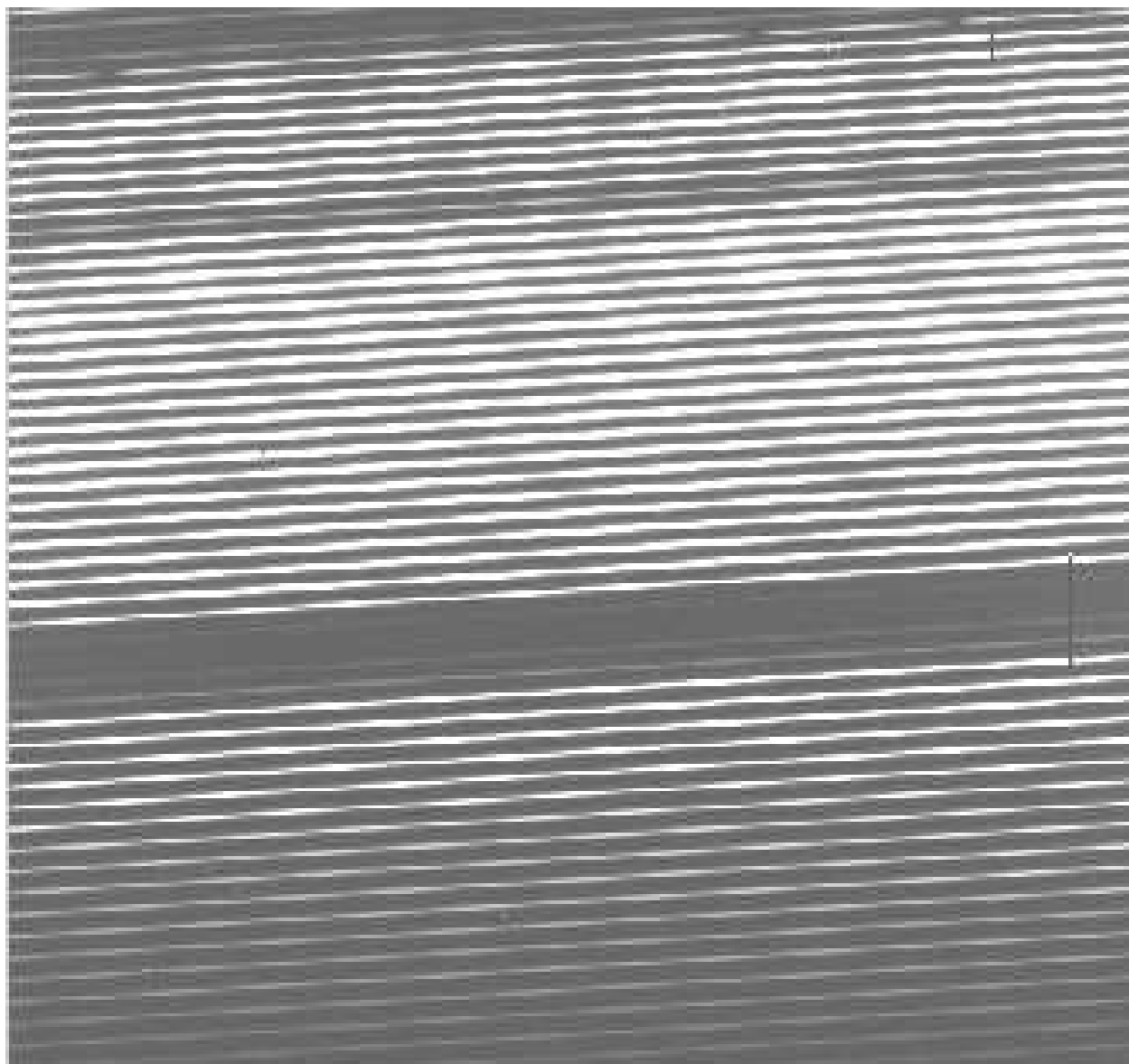


Fig. 4.—

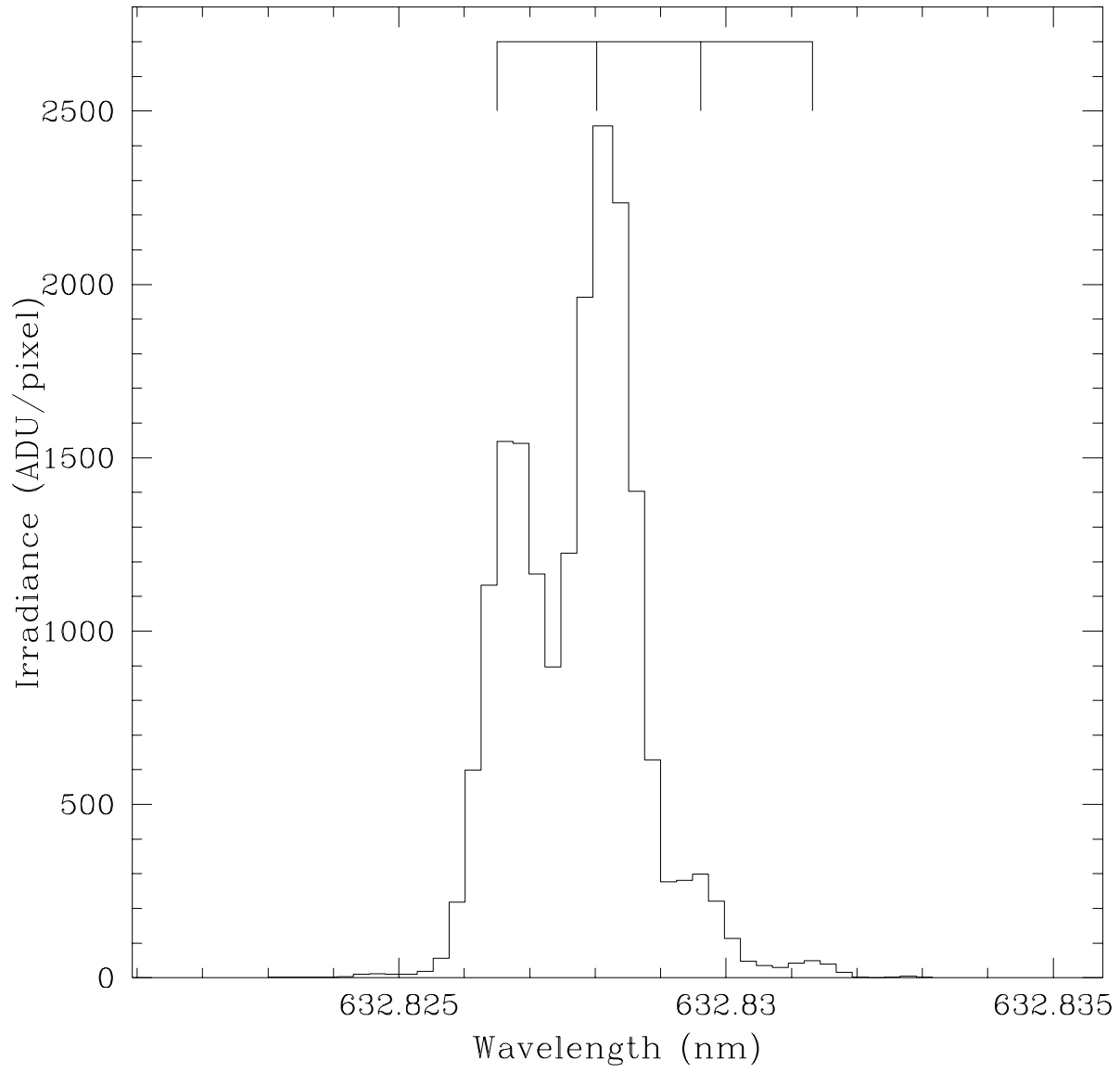


Fig. 5.—

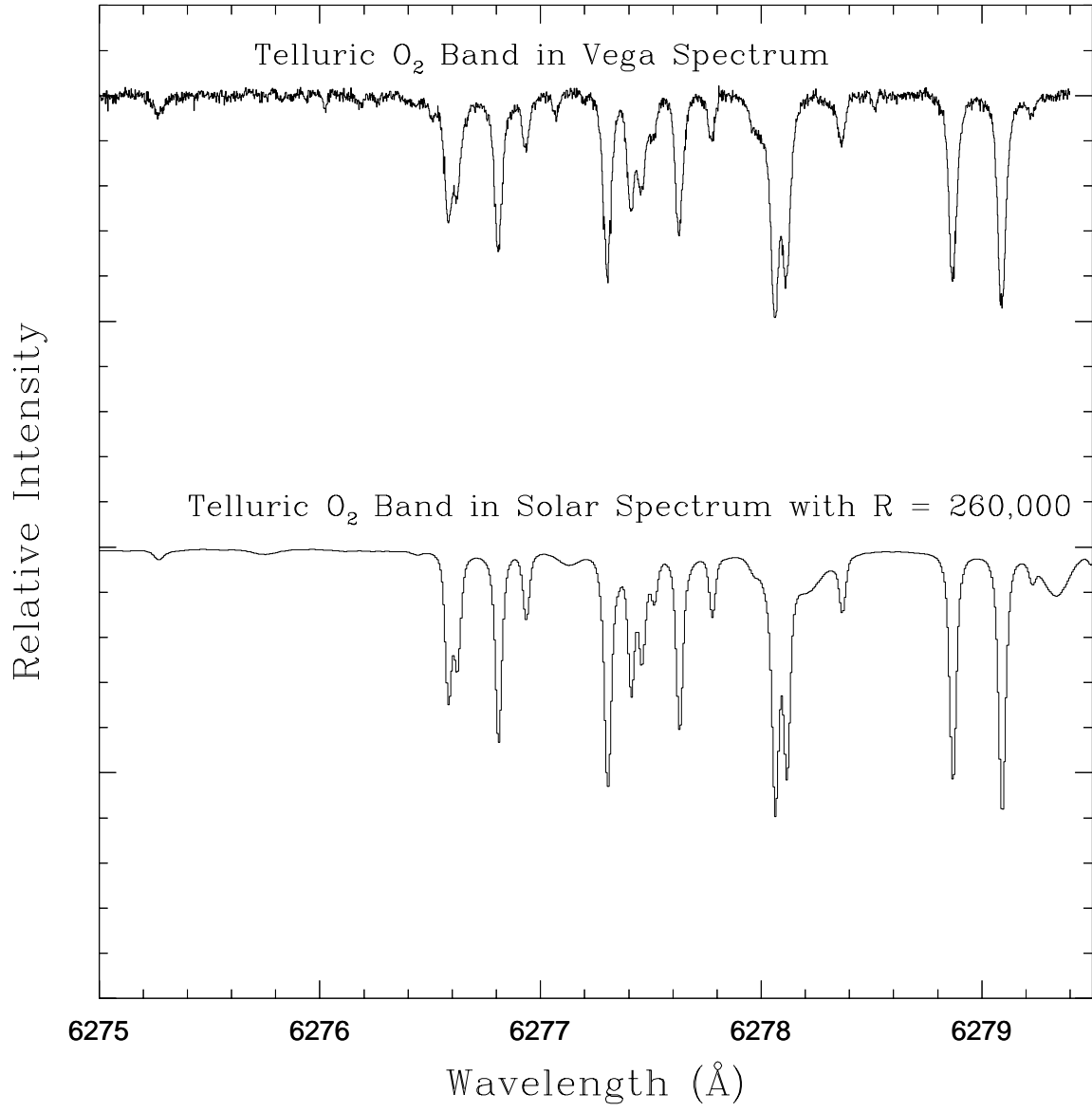


Fig. 6.—

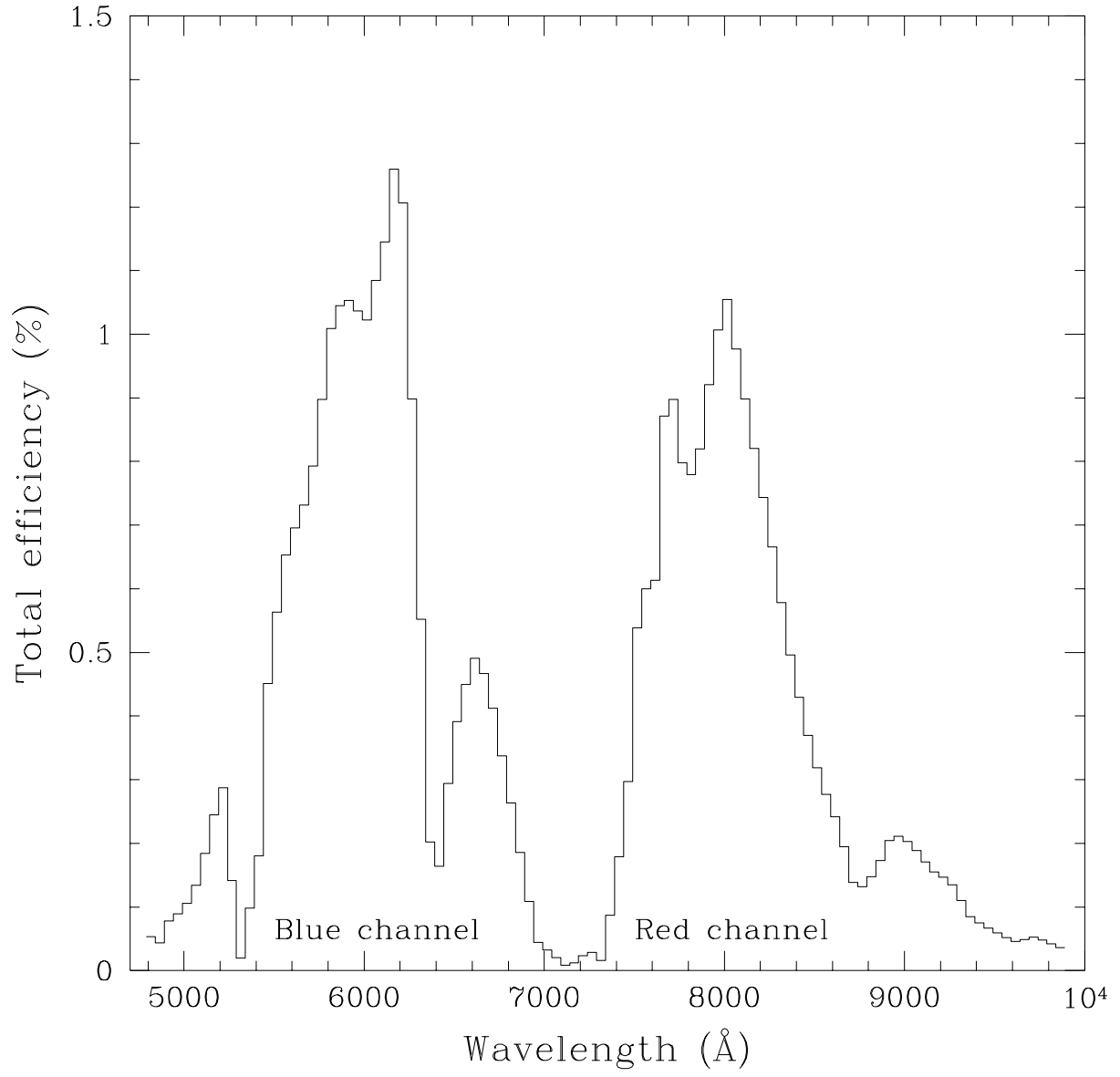


Fig. 7.—